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Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors

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A B S T R A C T

Flat plate photovoltaic/thermal (PV/T) solar collector produces both thermal energy and electricity simultaneously. This paper presents the state-of-the-art on flat plate PV/T collector classification, design and performance evaluation of water, air and combination of water and/or air based. This review also covers the future development of flat plate PV/T solar collector on building integrated photovoltaic (BIPV) and building integrated photovoltaic/thermal (BIPVT) applications. Different designs feature and performance of flat plate PV/T solar collectors have been compared and discussed. Future research and development (R&D) works have been elaborated. The tube and sheet design is the simplest and easiest to be manufactured, even though, the efficiency is 2% lower compared to other types of collectors such as, channel, free flow and two-absorber. It is clear from the review that for both air and water based PV/T solar collectors, the important key factors that influenced the efficiency of the system are the area where the collector covered, the number of passes and the gap between the absorber collector and solar cells. From the literature review, it is obvious that the flat plate PV/T solar collector is an alternative promising system for low-energy applications in residential, industrial and commercial buildings. Other possible areas for the future works of BIPVT are also mentioned.

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1. Introduction – technology overview

Many researches towards the solar energy occur all over the world due to the concern of global crisis on oil and gas prices. According to Deffeyes [1] and later, Bardi [2], oil has already started to peak. Sadorsky [3] mentioned that oil prices are often indicative of inflationary pressure in the economy which in turn could indicate the future of interest rates and investments, gas and coal reserves, in the other hand are larger than oil, it will latter tend to be progressively replaced by the former, which should attenuate a price explosion. Pareto [4] mentioned that this process will push

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energy prices higher, until sustainable sources replace dependency on fossil fuels as major source of energy. Constatntinos and Bouroussis [5] mentioned that the sustainable energy such as solar energy in a form of solar radiation has been identified as one of the promising source of energy to replace the dependency on other energy resources. The global need for energy savings requires the usage of renewable sources in many applications.

One of the renewable sources of energy is the photovoltaic solar energy (PV). As revealed by Hoffmann [6], the photovoltaic (PV) solar market has shown an impressive 33% growth per year since 1997 until today. Hybrid photovoltaic/thermal system in the other hand is the continuity of the photovoltaic solar energy system, it combined both systems into one system known as Hybrid photovoltaic/thermal (PV/T or PVT) solar system [7]. As reported by Zondag [8] and again by Prakash [9], the system can be segregated into two parts; the photovoltaic technology which derived from solar cell technology and convert into electricity, and thermal solar technology which derived from the thermal collector and convert the solar energy into heat. Bhargava et al. [10] mentioned that the hybrid system is operated solely by the solar radiation.

The solar energy technology or synonym as photovoltaic and solar thermal technology has many advantages and disadvantages comparing to others energy. The potential advantages such as:

- it works on noiseless environment; do not produce any unwanted waste such as radioactive materials;
- high performance and reliable system;
- clean technology – does not produce any toxic waste or radioactive material;
- highly credible system with life span expectation is between 20 and 30 years;
- low maintenance system.

The disadvantages:

- non-uniform cooling – need innovative absorber design;
- payback – less efficiency, longer payback period;
- production and installation cost–expensive and high cost;
- not suitable for integration with present roof system;
- need larger space for separate systems (hot water and electricity production).

According to Bakker et al. [11] the PV/T panels are an alternative and promising system concept for low-energy housing residential market. As revealed by Bazilian [12] the PV/T system from the technological point-of-view, are designed especially for low temperature applications due to that the combination of both systems needs to be compromise.

The objective of this paper is to compare each type of flat plate PV/T collectors on its design and performance. Besides that, this paper provides reviews of the latest development and the future work on the PV/T collector based on previous researcher's review paper [8,13,14].

1.1. Flat plate PV/T collector classification

As shown in Fig. 1, the flat plate PV/T collector can be classified into water PV/T collector, combination of water/air PV/T collector and air PV/T collector, depending on type of working fluid used. Further, the PV/T collectors can be distinguished by present of the absorber collector underneath the flat plate. A complete design of flat plate PV/T collector should comprised of a glass cover (glaze or unglazed), solar cell, encapsulated materials, and absorber collector underneath. The absorber collector plays important function in PV/T system. It cools down the PV cell or module, simultaneously collecting the thermal energy produced in the form of hot water or hot air. While this process occurs, the efficiency of the PV cell or module increases.

Aste et al. [15] mentioned that, amongst all types of PV/T solar collectors, the most popular PV/T collector is the PV/T air collector; nevertheless, this type of collector has less applications compared to the water collectors.

Zondag et al. [16] has elaborated the PV/T collector types. As shown in Fig. 2, the collector comprised of sheet and tube (1), channel (2), free flow (3) and two-absorber types (4).

It can be distinguished based on the flow pattern of the medium used, i.e. water and air or combination of both. For water type, it can be distinguished according to the water flow pattern and for air type, it can be distinguished according to the air flow configuration such as air above, below or on both side of the absorber collector and can be either single or double pass. Garg and Agarwal [17] mentioned that collectors are normally designed with pump and can be either forced or natural circulation.

The principal classifications of PV/T systems are similar to the PV system – it can be connected either grid-connected or standalone system. For grid-connected or utility-interactive, the systems are designed to operate in parallel with and interconnected with the electric utility grid. The primary component of grid-connected PV/T systems is the converter/inverter, or power

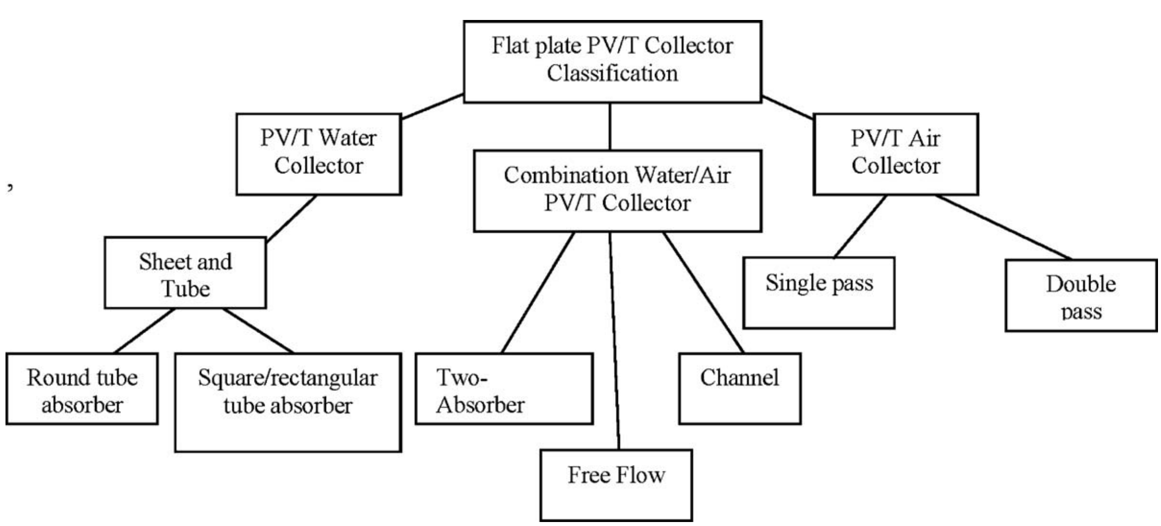

Fig. 1. Flat plate PV/T collector classification.

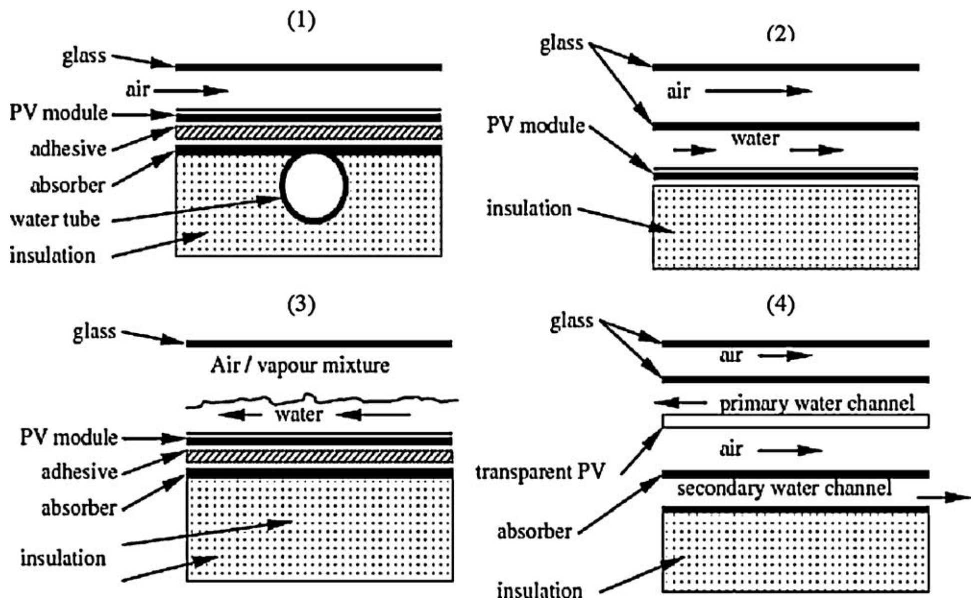

Fig. 2. Types of PV/T collectors [13,16].

conditioning unit (PCU) and thermal storage. For stand-alone, the systems are designed to operate independent of the electric utility grid, and generally designed and sized to supply certain DC and/or AC electrical loads. Talavera et al. [18] have compared both systems and made a suggestion that the grid-connected systems are more profitable investment when some economic conditions are fulfill.

2. PV/T collector design and performance evaluation

2.1. PV/T water collector

The problems such as low PV efficiency, architectural uniformity and limited space on roof for the installation of separate system have become important factors that influenced the idea of combining the PV/T system into one complete system. Bazilian et al. [19] mentioned that, one of the major disadvantages of PV cell, beside the high cost, is the problem with low efficiency. The typical commercial PV cells are only converting between 6 and 8% of the incident radiation into electrical energy and balance remains as a lost either by reflection or as heat that penetrated into the PV cell. Fig. 3 shows a schematic diagram of grid-connected PV/T water system with PV/T collector, thermal storage, auxiliary heater and converter/inverter (grid-connected).

Earliest study on PV/T water collector has been performed by Florschuetz [20], who extended from Hottel–Whillier model [21] to the analyzed the combination of PV/T flat plate collectors. As mentioned by Zondag et al. [22], by combining the PV/T collector will answer the problems such as electrical efficiency increasing due to the cooling effect, provide more architectural uniformity by aesthetical design and finally, minimized the usage of space on roof will reduce the payback period. Tiwari and Sodha [23] also mentioned that by combining both systems into one system, shows significant effect on the efficiency gained.

Beside the experiment, many simulation studies have been performed to justify the PV/T water collector system. As such, a simulation of Photovoltaic/thermal collector (PV-TC) for domestic heating and cooling has been conducted by Christandonis [24] in Island of Rhodes. In this simulation, they compared the efficiency of the system to the conventional solar collector and concluded

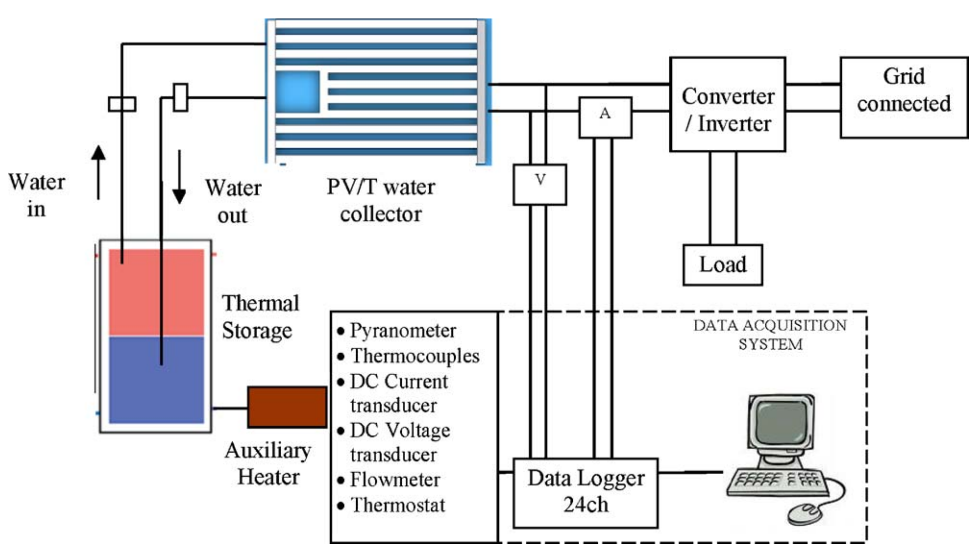

Fig. 3. Schematic diagram of PV/T water based system.

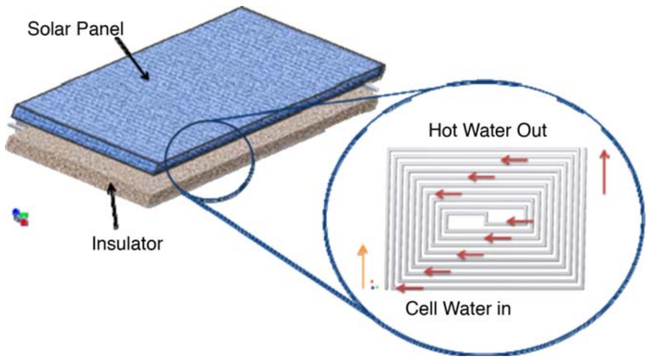

Fig. 4. PV/T water collector design with collector absorber underneath the solar panel [26].

that the overall efficiency of the system is about 9% lower than the efficiency of conventional solar collector; provide a remarkable percentage of domestic heating and cooling demands in the region of Rhodes.

In term of cell materials performance, Zakharchenko et al. [25] from Mexico have deployed different kind of panel materials such as crystalline (c-) Si, α-Si and $CuInSe^2$. They also constructed a collector and studied has been performed to investigate the thermal contact between the panel and the collector. They concluded that a special design involving heat extraction need to be perform enable to extract more heat and increase it thermal and electrical efficiencies. Fig. 4 shows the example of a complete water PV/T collector design with an absorber collector underneath the PV cell (solar panel).

2.1.1. Sheet and tube concept

2.1.1.1. Round tube absorber. As mentioned by Charalambous et al. [13], the design of sheet and tube concept is the easiest to manufacture and only 2% less efficient compared to other types of collector. A physical model of hybrid PV/T system has been investigated by Bergene and Lovvik [27] incorporate with the algorithms for the quantitative predictions on the performance of the system. The model is produced based on the analysis of energy transfer due to conduction, convection and radiation. They claimed that this model can be use to predict the amount of heat drawn out from the system and the power output. They utilized the sheet and tube concept for the system together with the fin. They concluded that the system efficiency is interesting to investigate and algorithms can be used as the simulation to this system. The model predicts the performance of the system efficiency of 60–80%.

An annual exergy evaluation on PV/T hybrid collector at Science University of Tokyo has been performed [28]. As shown in Fig. 5, they specially designed and constructed a hybrid collector made of non-selective aluminium hollow round tube shape as an absorber collector. They developed PV/T collector using a single cover system. In the design, they constructed the PV/T collector comprised of flat box with glass cover on top, solar cell, absorber collector in the form of aluminium roll bond with fluid conduit. Underneath the absorber collector, the glass wool was used as a heat insulating material.

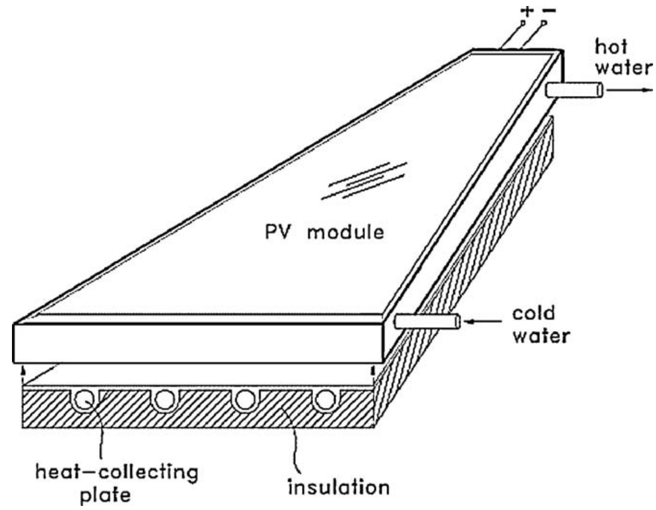

Fig. 6. Integrated photovoltaic/thermal system (IPVTS) with round tube channel [30].

An experiment has been conducted in Saudi Arabia to evaluate the hybrid system of PV/T system using sheet and tube shape as the absorber collector [29]. They utilized thick copper sheet and black paint coated copper pipe as a tube, which later connected to the 440 W PV panels. The outcome of this experiment is the production of both electricity and hot water. They concluded that the PV/T system is not adaptable to the Saudi Arabia environment due to the high ambient temperature during summer. The high ambient temperature affects the PV operation even it produce good thermal efficiency.

The performance study to evaluate and understand the integration of solar photovoltaic and thermal systems has been conducted by Huang et al. [30]. In the study, they compared the conventional solar water heater with the PVT system knows as Integrated photovoltaic/thermal system (IPVTS). As shown in Fig. 6, the polycrystalline PV module has been integrated with the thermal collector made from a corrugated polycarbonate panel with sheet and tube heat collecting plate made of copper. They concluded that the solar PV/T collector made from corrugated polycarbonate panel produced good thermal efficiency. They suggested that further improvement can be achieved by proper insulation for the PV/T design.

Experimental work using a TerraSolar's low cost a-Si thin film solar cell modules integrating with hybrid flat plate PV/T

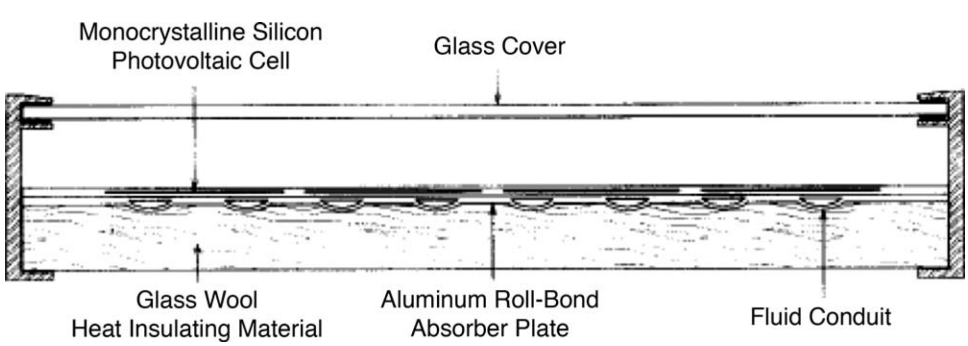

Fig. 5. Cross-section of the PV/T collector [28].

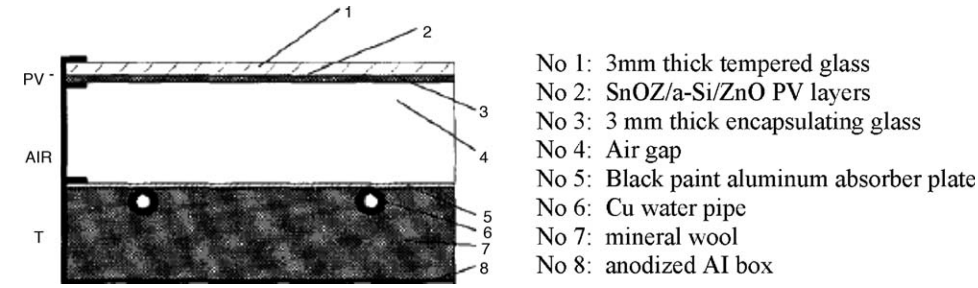

Fig. 7. Cross-section of low cost a-Si thin film solar cell modules integrating with hybrid flat plate PV/T [31].

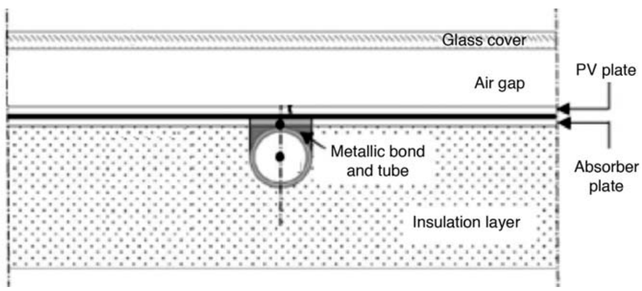

Fig. 8. Cross-section of single glazing PV/T water collector [32].

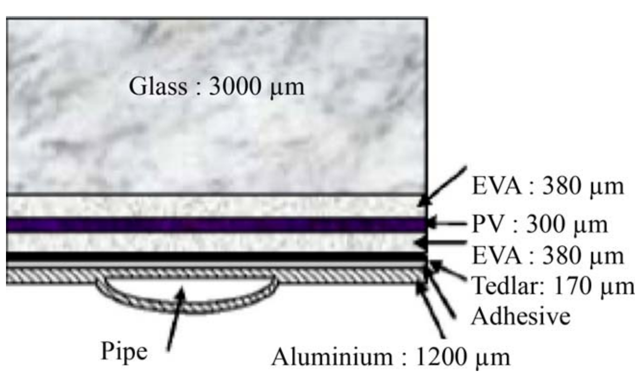

Fig. 9. Cross-section of hybrid solar panels of polycrystalline silicon cells and heat exchanger [33].

module has been conducted by Staebler et al. [31]. As shown in Fig. 7, a copper pipe has been utilized using a sheet and tube concept and recorded a thermal efficiency of 32.5% at the beginning of the experiment even though the water output temperature recorded at 30.2 °C. They concluded at the end of this experiment, the absorber collector reached an average maximum temperature of 52 °C, with 117.25 W of thermal power and the efficiency of 18.6%.

Chow [32], as in Fig. 8, has developed an explicit dynamic model of a single glazed flat plate water heating PV/T collector using a sheet and tube concept. He discovered that the fin efficiency and bonding quality between the collector and the sheet underneath the cells (module), as the crucial factors, which often bring limitations to the overall efficiency achievable. The fin, in a form of metal tube, is normally connected to the PV module using a metallic bond enable the heat to be transfer, this will ensure "zero gap" or "no gap" condition between the metal tube and PV module.

Boddaert and Caccavelli [33] have designed and developed hybrid solar panels that consist of polycrystalline silicon cells and heat exchanger. As shown in Fig. 9, the cheap roll-bond technology using aluminium is specially designed with a hollow tube (sheet and tube concept) in the middle of it act as the heat exchanger system underneath the PV module.

Kalogirou and Tripanagnostopoulos [34] using TRNSYS to simulate the hybrid PV/T solar system for domestic hot water and electricity production made of sheet and tube concept. They simulate the system using the polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) module type combines with the solar collector plate. In the simulation, they have deployed the typical flat plate of solar collector and absorber collector made of copper material. The transparent cover has been used in this simulation. The purpose of the transparent cover, firstly to reduce the conduction losses from the absorber collector through the restraint of the stagnant air layer between the absorber collector and the glass and secondly to reduce the radiation losses from the collectors.

Again, Kalogirou and Tripanagnostopoulos [35], as shown in Fig. 10, produced a hybrid PV/T systems consist of PV modules made from polycrystalline and amorphous solar cells with heat extraction unit mounted together using the copper sheet and pipes concept. The application aspects in the industry of PV/T systems

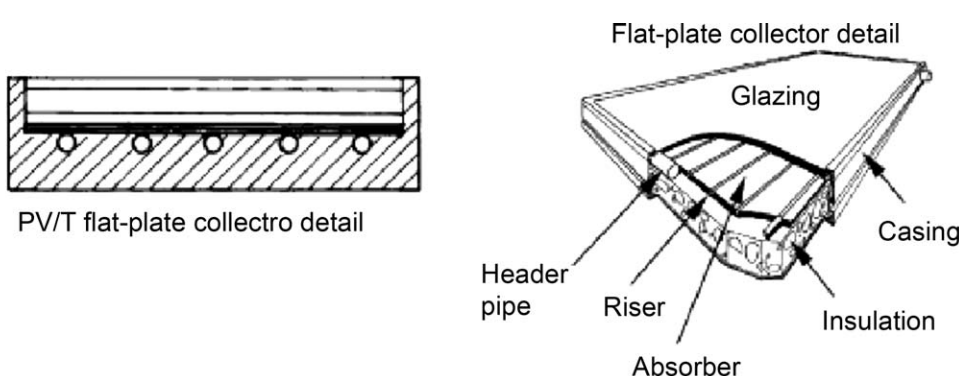

Fig. 10. Cross-section of hybrid PV/T solar collector [34,35].

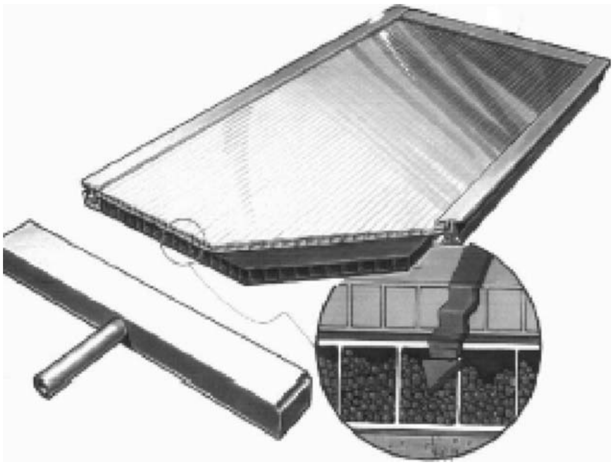

Fig. 11. Cross-section of PV/T collector made of polymer square tube of polyphenylenoxid (PPO) plastics material [36].

with water heat extraction has been studied thoroughly and analyzed with TRNSYS program. The study includes the industrial process heat system that operated at two different (load supply) temperatures. The result shows that the electrical production using polycrystalline solar cell is more than when using amorphous solar cells but in term of solar thermal fraction gives slightly lower results.

2.1.1.2. Square/rectangular tube absorber. Sandnes and Rekstad [36] have performed the experimental and analytical model for PV/T collector. In this experimental, a polymer absorber collector is combined with single-crystal silicon PV cell and assembled it as a hybrid energy generating system. The system simultaneously produced low temperature heat and electricity. The absorber collector, as shown in Fig. 11, has been made from polymer square tube of polyphenylenoxid (PPO) plastics material with black surfaces contains internal and wall to wall channels filled with ceramic granulates. Fluid (water), as the heat carrier, is pumped inside the internal distribution channel by force of gravity flows down through the parallel absorber channels. The results are compared with simulation results and shows almost identical results.

Chow et al. [37,38] have conducted an experiment of PV/T collector system for domestic application in China. In this experiment, an aluminium-alloy flat box with square or rectangular shape channel has been designed and constructed. The test results show high efficiency on combined system achieved with primary energy saving for daily exposure approaches 65% at zero reduced temperature operation. Another experiment (Fig. 12) on hybrid photovoltaic-thermosyphon water heating system for residential application with natural circulation of water has been performed and found that the final temperature of hot water produced higher after 1-day exposure [39].

Similar experiment has been performed using an aluminium-alloy flat box, with square or rectangular shape channel together

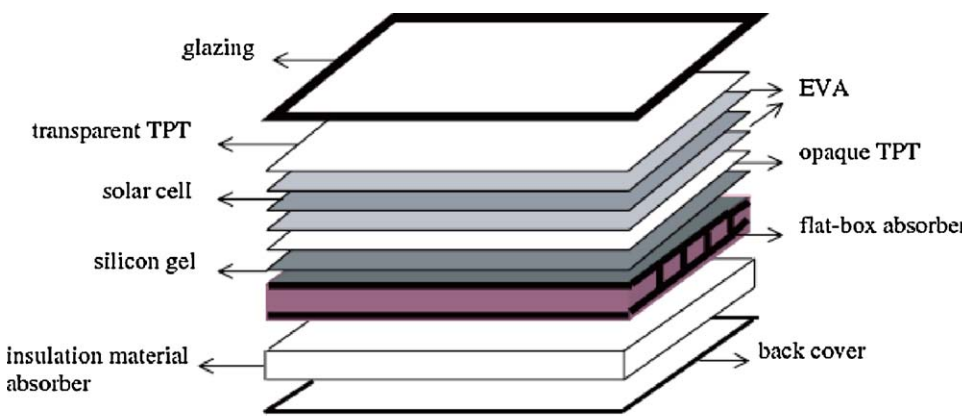

Fig. 12. The constituent layer of hybrid-thermosyphon water heater system [39].

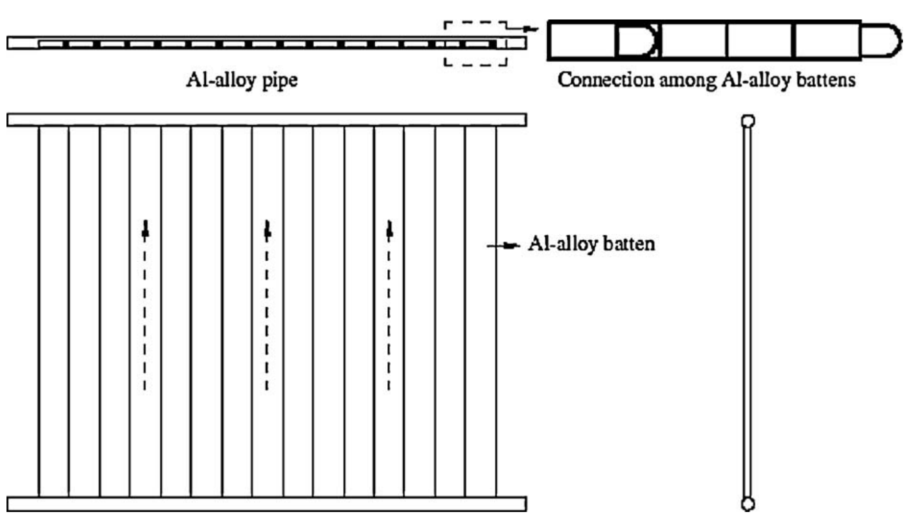

Fig. 13. Construction of flat box Al-alloy absorber collector for hybrid PV/thermal water heater system [40,41].

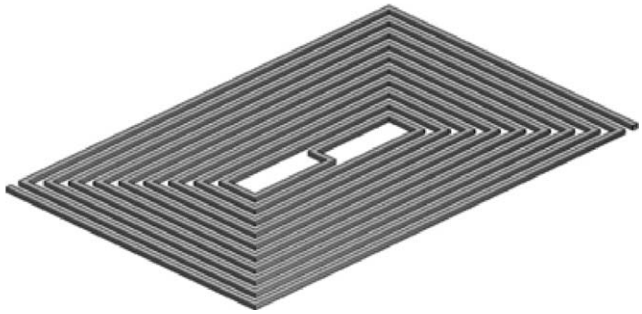

Fig. 14. Construction of spiral flow design [42].

with polycrystalline silicon cells utilized water as a coolant for cooling purposes. From this experiment, they conclude that the thermal efficiency reached around 40% when the initial temperature in the system is same as the daily mean ambient temperature [40].

As shown in Fig. 13, another experiment on natural circulation hybrid PV/T water heating system has been constructed and tested [41]. In this experiment, sensitivity study of the system has been performed and proved that by combining the systems, the installation area produce more energy per unit surface area than one PV panel and one hot water system (thermal collector).

Performance simulation of PV/T collectors with different absorber collectors design has been studied [42]. In this simulation, seven new design configurations of absorber collectors have been designed and compared. The design shapes of the absorber collectors are either square/rectangular or round hollow tube. Simulation has been conducted to analyze the parameters of the collectors such as the solar radiation, ambient temperature and mass flow rate. The simulation results shows that the best design configuration is the spiral flow design (Fig. 14), with thermal efficiency of 50.12% and cell efficiency of 11.98%.

2.2. Combination of water and/or air PV/T collector

Combination of water and/or air type collectors can be distinguished according to the flow pattern of the water or air. In water type PV/T collectors, the important parameters that need to be taken into consideration such as sheet and tube, channel, medium (fluid) flow and the absorber collector types. Water type PV/T collector has been discussed thoroughly in Section 2.1. For air type PV/T collector, the main parameter is the flow pattern of the air. It can be either on top, underneath or both side of the absorber collector and can be in single or double pass collectors.

Another comparative study has been prepared by Zondag et al. [16] from Netherlands. The concepts of sheet-and-tube, channel PV/T, free flow and two-absorber PV/T-collectors are investigated. The results show that the combined PV/T collectors provide the efficiency of over 50%. For uncover collector, the thermal efficiency is 52% and thermal efficiency of single cover sheet and tube design is 58% and finally for channel above the PV design, the thermal efficiency is 65%. Later, Zondag and van Helden [43] performed another research on PV/T system that utilized the heat. In this research, various PV/T modules types such as with or without cover, air or water type, closed or open loop systems have been studied and the results are presented in system calculations for PV/

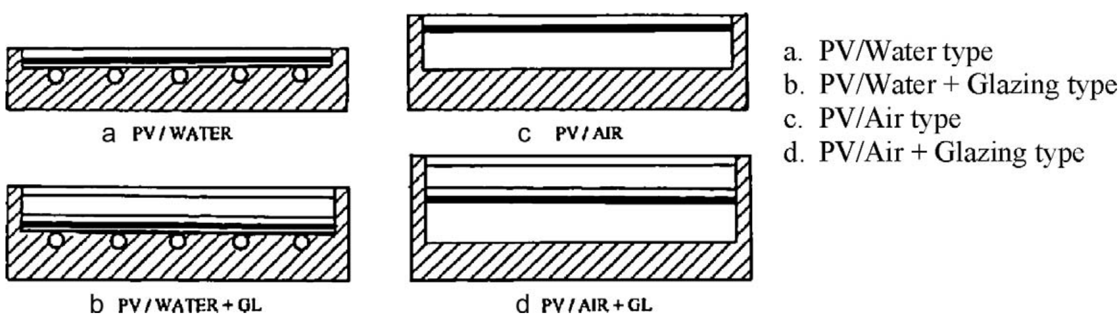

Fig. 15. Cross-section of the PV/T experiment model [44].

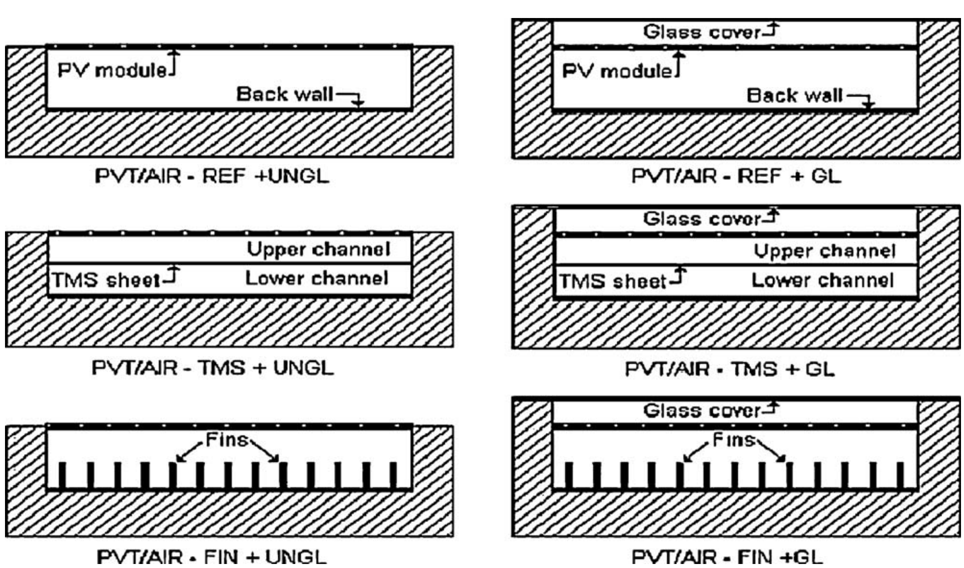

Fig. 16. Cross-section of PV/T collector models [46].

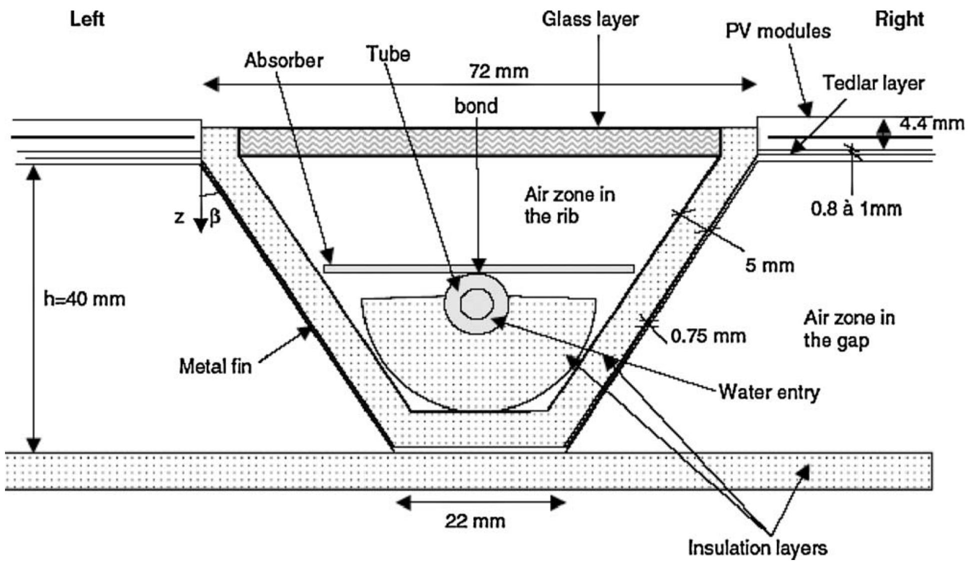

Fig. 17. Cross-section of bi-fluid PV/T (water and air) collector [47].

T roof domestic systems. They concluded that the PV/T water collectors have a better performance than PV/T air collectors and covered closed loop systems performed better than uncovered closed loop systems.

2.2.1. Two-absorber

A comparative experiment of Hybrid PV/T has been performed by Tripanagnostopoulos [44]. As shown in Fig. 15, it consists of photovoltaic modules with thermal collectors. In this experiment, a commercial pc-Si has been compared to the a-Si PV modules. Besides that, this experiment also comparing the parameters such as PV and water, PV sand air, PV water with glazing and PV air with glazing. The experiment has been conducted outdoor and the results of thermal efficiency, in steady state condition, shows that the pc-Si PV module produced higher electrical efficiency compared to a-Si PV module. The results also shows that the electrical efficiency of PV/water is higher by 13.3% that other systems. This experimental work also proved that when the PV is cooling, the electrical efficiency increases and simultaneously increase the overall efficiency.

Tonui and Tripanagnostopoulos [45] performed another experiment to improved PV/T solar collector with heat extraction by forced or natural air circulation. In this experiment, the study comprised of the possibility of generating electricity and heat energy from commercial PV module adopted as a PVT/AIR solar collector either with forced or natural flow.

Another development of combination of water and air type of PV/T collector has been designed by Tonui and Tripanagnostopoulos [46]. As shown in Fig. 16, they designed the system that utilized both water and air to produced hot water and at the same time produced hot air simultaneously. They exploited the thin flat metal sheet with finned back wall of air channel, suspended in the middle of the system. In this experiment, they investigated the effect of the channel depth, channel length and mass flow rate on electrical and thermal efficiency for both water and air. They claimed that the PV/T water based collector is more efficient that PV/T air based collector due to the high thermo-physical properties of water compared to air, which generally low with the maximum thermal efficiency obtained, is about 52% and 9–10% for the electrical efficiency, giving the total efficiency of about 61–62%.

A simplified steady state two-dimensional mathematical model of bi-fluid PV/T (water and air) collector with a metal absorber collector has been developed and constructed by Assoa et al. [47]. They designed a channel shape of a ribbed sheet steel absorber collector. Simulation has been performed and compared it with the experiment. The experiment, as shown in Fig. 17, consists of a photovoltaic solar air collector with ribbed sheet steel absorber. The PV module is made from polycrystalline material (240 mm × 1980 mm) is fixed through a thin layer of tedlar and later fixed to the rib. The rib includes an insulation layer of polystyrene and covered with thin reflective layer and circulation pipe for water circulation. They concluded that the solar collector mass flow rate have influenced on the solar air collector behavior due to some thermal losses exist between the solar air collector and the solar water collector. They suggested improving the bi-fluid PV/T collector design by study on the insulation material and improving the design of the collectors. The solar collector performance study shows that the thermal efficiencies are able to reach approximately 80% based on specific collector length and mass flow rate.

Energy performance of water hybrid PV/T collectors applied to the combisystems has been studied by Fraisse et al. [48]. The combisystems, in fact, are the integration of PV modules with thermal, which later combined with ‘‘Direct Solar’’ floor. In this study, water has been used as a heating element and hot water supply to the house. The combisystem, has been installed in Macon

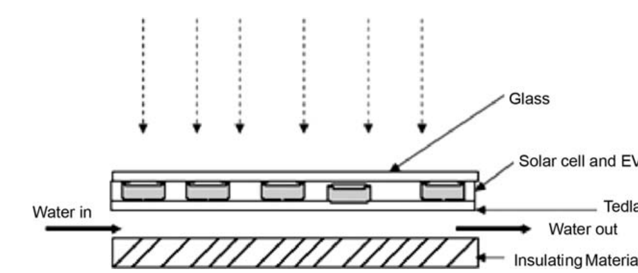

Fig. 18. The cross-section of integrated photovoltaic and thermal solar system (IPVTS) [49].

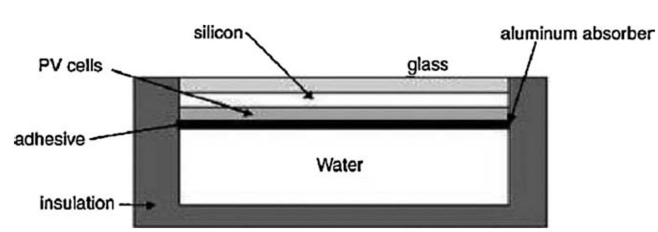

Fig. 19. Cross-section of PV/T collector [50].

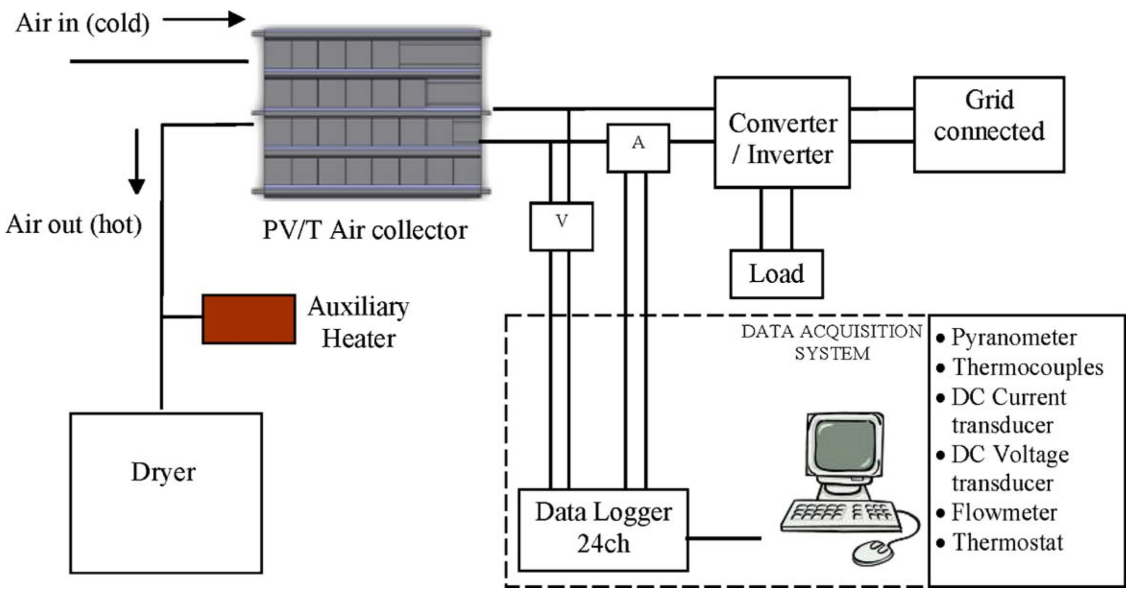

Fig. 20. Schematic diagram of PV/T air based system.

area in France, without PV glass cover, produced efficiency of 10% which is 6% better than a standard module.

2.2.2. Channel and free flow absorber

The combination of water and air type of PV/T collector system which is known as integrated photovoltaic and thermal solar system (IPVTS) has been developed by Tiwari and Sodha [49]. As shown in Fig. 18, an integration of photovoltaic and thermal solar–water or air based system has been developed. They deployed and configured four systems, which are; the unglazed with tedlar, glazed with tedlar, unglazed without tedlar and glazed without tedlar. During this experiment, they compared the PV/T system with water and air heater that passing through channels. The results from the experiment have proven that the daily efficiency of the system of water is higher than air for all configuration except glazed without tedlar. The data shows that the overall thermal efficiency of the system during summer and winter conditions is approximately 65% and 77%.

Rosell et al. [50] have designed and simulated the low concentrating PV/T channel system coupling with linear Fresnel concentrator. The prototype, as shown in Fig. 19, is known as 11X, has been developed in University of Lleida equipped with two axis tracking system and the channel made of opaque PV cells. The experiment result shows a total efficiency of over 60% achieved.

As reported by Charalambous et al. [13] based on the comparative study conducted by Zondag et al. [16] observed that all channel concepts have slightly higher efficiency when compared to the sheet and tube due to better heat transfer characteristics of channel.

For free flow panel, that consists of air on top, fluid in the middle and the cell underneath, with air and fluid separated by transparent glass layer, Charalambous et al. [13] mentioned since the air and fluid are separated with the transparent glass layer therefore, the evaporation strongly reduces the thermal efficiency and condensate on the top of the glass causes additional reflection.

2.3. PV/T air collector

As shown in Fig. 20, the thermal energy is produced from the heat that derived from the PV/T collector in the form of hot water

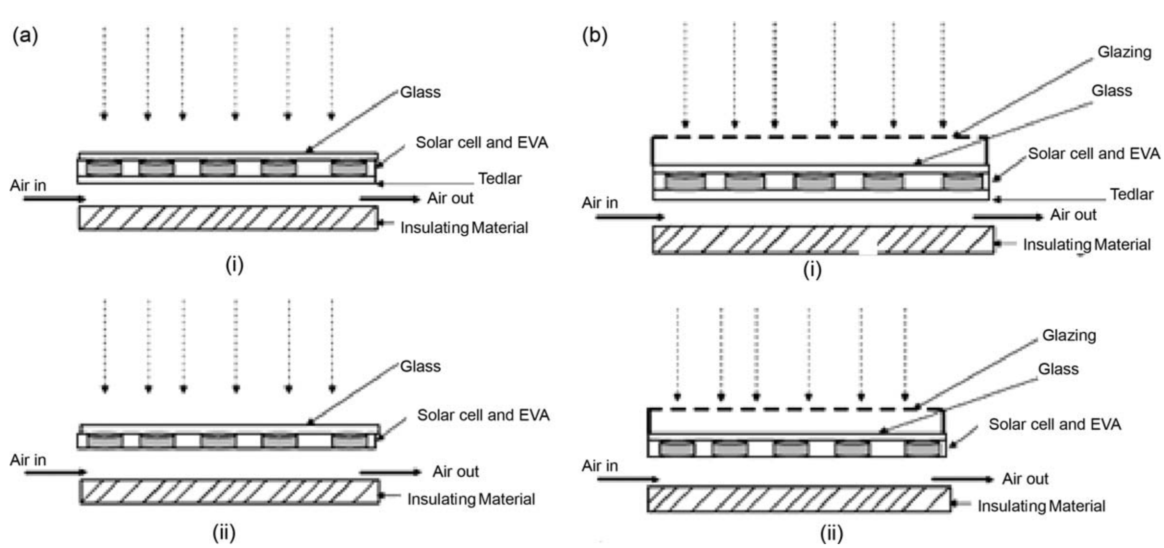

Fig. 21. Cross-section of unglazed PV/T air (a): (i) with tedlar and (ii) without tedlar and (b): (i) glazed with tedlar and (b)(ii) without tedlar [54].

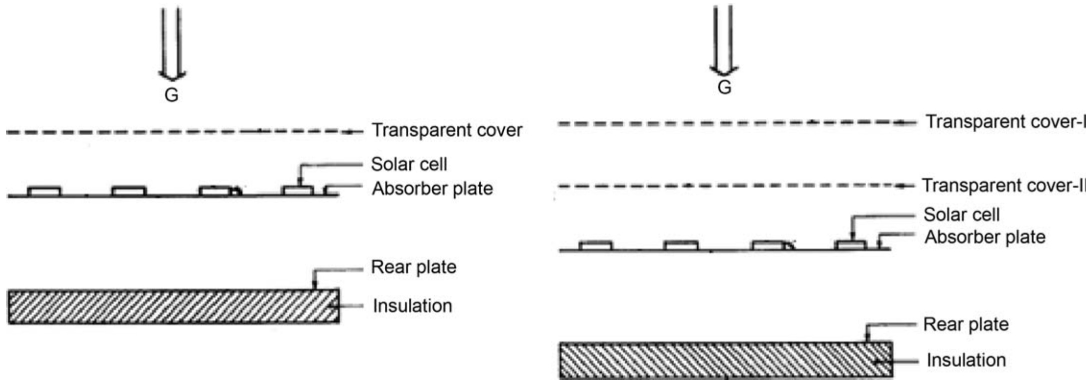

Fig. 22. Schematic configuration of conventional PV/T air heating collector (left) single glass configuration (right) double glass configuration [55].

or hot air. Hot air produced from this collector, in this case, it can be use for many applications such as clothes and agricultural/herbs drying such as cocoa, ginseng, and beans.

The agriculture/herb drying is crucially important to the food industries. With the unstable condition of hot and humid climate, especially in tropical countries, the PV/T air collector has become the best solution to obtain superior quality of drying product. Othman et al. [51] mentioned that the use of solar dryers of PV/T air collector will enhanced the environment, wealth creation and nation building as well as sustainable development for the country. Janjai and Tung [52] and Fudholi et al. [53] revealed that drying for agricultural and marine products are considered to be the most attractive and cost effective applications for solar energy.

As in Fig. 21,Tiwari and Sodha [54] have performed evaluation on the overall performance of unglazed and glazed hybrid PV/T air collector with or without tedlar. The numerical computations have been carried out for composite climate in New Delhi, India and the results are compared. From their observation, they concluded that the glazed hybrid PV/T without tedlar gives the best performance compared to all configurations being evaluated.

Garg and Adhikari [55] as in Fig. 22, have performed the steady-state simulation on the conventional hybrid PV/T collector of single and double-glass covers of PV/T air heating system. They conclude that the parametric studies of PV/T air collector shows that influence of efficiency to the collector length and area, mass flow rate and duct depth.

Solanki et al. [56] has performed an indoor simulation and testing of PV/T air collectors. They developed a system for thermal and electrical of PV/T solar air heater that connected in series. The experimental results show that the thermal efficiency gained is 42% and electrical efficiency is 8.4%.

There are several designs of PV/T air collector system but the main designs focusing in this paper are the single pass and double pass PVT solar collector that manipulated the air as the heat transfer medium. Studied performed by Sopian et al. [57] shows that the double pass PVT solar collector performed higher efficiency comparing to single pass PVT solar collector.

2.3.1. Single pass PV/T air collector

Mathematical model of single pass PV/T air collector (PVT) with compound parabolic concentrator (CPC) and fins has been performed by Alfegi et al. [58]. The model concentrated on both sides (top and bottom sides) of the absorber collector to predict the thermal and combined PV/T performance. As shown in Fig. 23, air has been used as the working fluid that flows between top glasses of the absorber collector to the bottom plates of the absorber. Results at solar irradiance of 400 W/m^2 shows that the combined PV/T efficiency increased from 26.6% to 39.13% at mass flow rates varies from 0.0316 to 0.09 kg/s.

A comparison study has been performed to investigate the effect of mass flow rates on the thermal and electrical efficiencies of the hybrid collectors [26]. As shown in Fig. 24, a single pass rectangular tunnel absorber collector has been designed and compared with spiral flow absorber collector as in Fig. 4. The single pass rectangular tunnel has been designed to generate hot air and electricity while the spiral flow has been designed to generate hot water and electricity. Both absorber collectors were fixed underneath the flat plate single glazing sheet of polycrystalline silicon PV module. The experiment results shows that the single flow absorber collector generates combined PV/T efficiency of 64% with electrical efficiency of 11% and power maximum output of 25.35 W and single pass rectangular tunnel absorber collector generated combined PV/T efficiency of 55% with electrical efficiency of 10% and maximum power output of 22.45 W.

The performance effect of the air flow rate for single pass, double duct PV/T with finned, has been studied [59,60]. Fig. 25 shows the experiment with photovoltaic cells placed on top of the fin. The experiment has been conducted to investigate the effect of the mass flow rate of the system. Results show that with the fin attached underneath, the PV increased its efficiency from 49.135%

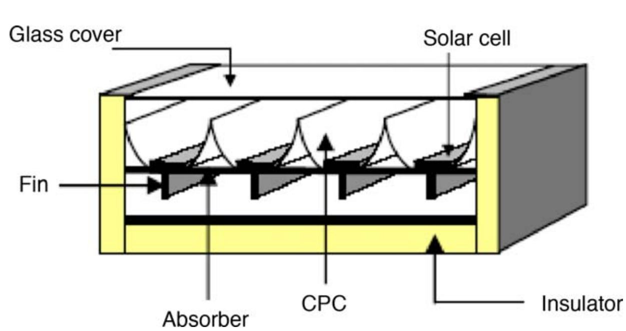

Fig. 23. Cross-section of a single pass PV/T air collector (PVT) with Compound Parabolic Concentrator (CPC) and fins [58].

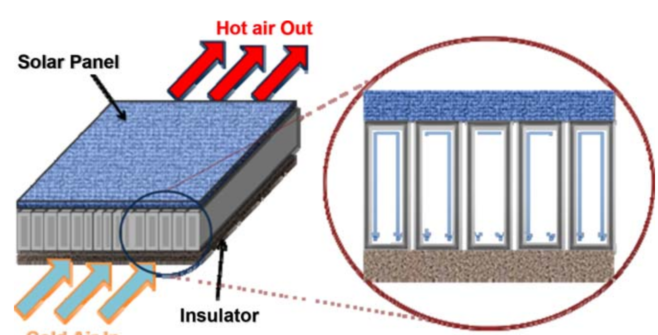

Fig. 24. Cross-section of PV/T air collector with rectangular shape absorber collector design [26].

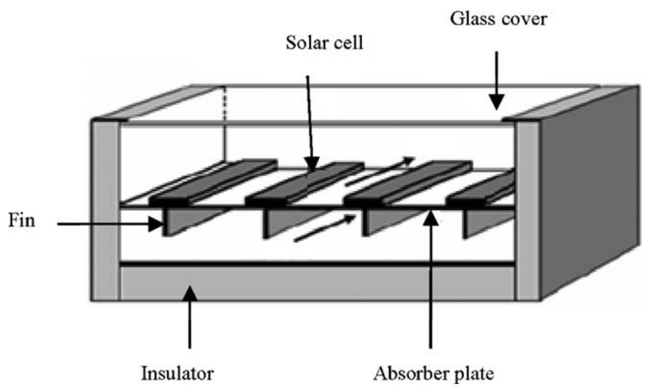

Fig. 25. Cross-section of single pass PV/T with finned of double duct PV/T air heaters [59,60].

to 62.823% at mass flow rates various from 0.0316 to 0.09 kg/s, solar radiation of 600 W/m2 and inlet temperature of 35 °C.

Another design of single pass PV/T collector has been designed by Othman et al. [51,61]. The PV/T collector, as shown in Fig. 26, has been designed with v-groove shape and placed underneath the PV plate. Air has been used as the heat transfer medium to transfer heat out. During the experiment, flow rate (speed) air ranging from $69.6 \pm 2.2 \times 10^{-4}$ kg/s to $695.8 \pm 2.2 \times 10^{-4}$ kg/s has been passed through the v-groove. The result shows that by adding the v-groove to the design, the PV/T increased its efficiency of 30% higher when compared to other type of PV/T collectors.

An experiment on a single pass PV/T with rectangle tunnel absorber has been developed [62]. The rectangle tunnel, as shown in Fig. 27, acted as an absorber collector has been fixed underneath the photovoltaic panel. The main purposed of the experiment is to identify the suitable air flow for cooling the PV panel. By doing this, will increase the efficiency of the panel. The results shows that the combined PV/T efficiency of 64.72% and thermal efficiency at 54.70% with solar irradiance of 817.4 W m^{-2}, mass flow rate of 0.0287 kg s^{-1} at ambient temperature of 25 °C. They concluded that the hybrid PV/T with rectangle tunnel as heat absorber shows higher performance compared to conventional PV/T system.

2.3.2. Double pass PV/T air collector

A double pass PV/T solar air collector, as shown in Fig. 28, suitable for solar drying applications has been developed and tested [63]. They claimed that the steady state solution to determine the outlet and mean photovoltaic panel temperature has been obtained based on differential equations of the upper and lower channels of the collector. The result from the experiment shows that the thermal efficiency obtained is 60% with mass flow rate of 0.036 kg/s, global solar radiation level of 800 W/m^2 and expected temperature rise to 188 °C. The performance of solar collector with fins can be further improved by fixing the parabolic concentrator to the collector.

Performance analysis of a double pass PV/T solar air collector with fins has been studied further [60,64–66]. In their study, the concentrating reflectors have been used to increase the power produced from the solar cell. They proved that by installing fins at the back of the collector will improve the heat transfer of the collector. As shown in Fig. 29, the collector consist of three main components: glass cover on the top, panel with photovoltaic cells and absorber collector at the bottom. Air was flow through the upper part of glass cover and PV panel and passing through the lower part of PV panel. The fins has been fabricated using aluminium sheet to increase the capability of extracting heat from PV cells thus increase the efficiency of the collector.

The double pass PV/T solar air collector with fins and compound parabolic concentrator (CPC) has been performed by Othman et al. [66] to study the performance over a range of operating conditions. They adding the CPC to enhanced electrical and thermal energy output from the collector. They also add the fin to encountered the problem with poor performance of solar cells at high operating temperatures. As shown in Fig. 30, the air flow behavior, behave as the same way of the collector with fins but with CPC, the solar irradiance is increased. Fins attached underneath the PV cells help removed the heat from PV cells.

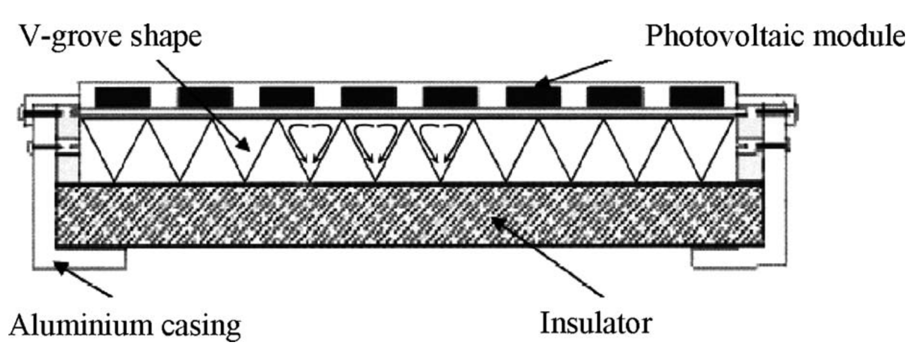

Fig. 26. Cross-section of PV/T collector with v-groove [51,61].

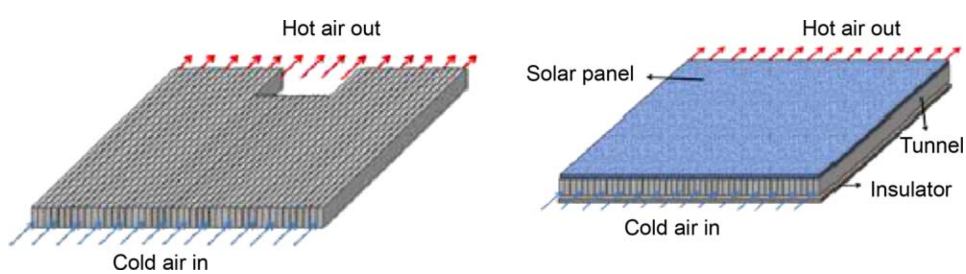

Fig. 27. Single pass PV/T with rectangular tunnel design [62].

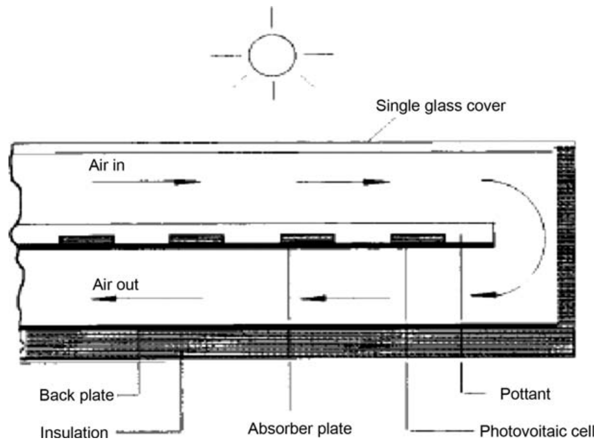

Fig. 28. Cross-section of double pass PV/T solar collector [63].

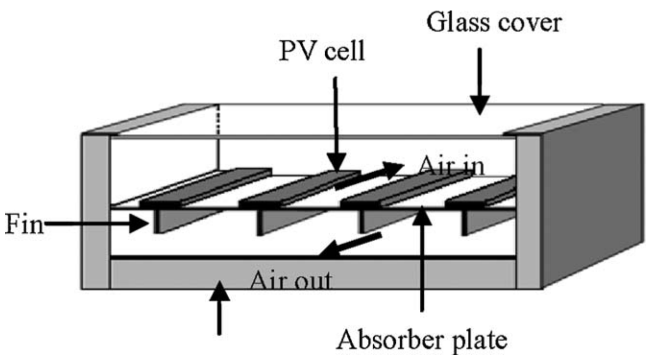

Fig. 29. Cross-section of double pass PV/T solar collector with fins [60,64–66].

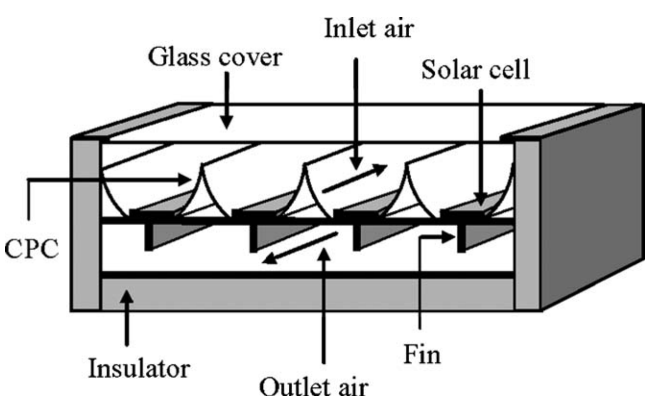

Fig. 30. Cross-section of double pass PV/T solar collector with fins and CPC [66].

3. Future development of PV/T collector

3.1. BIPV and BIPVT

Building integrated photovoltaic (BIPV) systems are designed not only to generate electricity but also generate heat. The heat is considered to be a waste to the system and also reduces the efficiency of generation. Crawford et al. [67] have combined a heat recovery unit and analyzed it with two types of photovoltaic cell. The first system comprised of two c: Si 75 W with PV modules made of aluminium frames and fixed to the timber rafters. The second system was identical to the first system with the addition of a heat recovery unit. They concluded that the energy payback periods between 4 and 16.5 years were found, depending on the BiPV system.

The comparative study on building integrated PV technology has been performed [68]. The concept of building integrated PV technology, integrate the PV with the building facade. In this study, they have developed computational model of mono-crystalline silicon PV wall and later installed it at 30 storey building (hotel) in Macau, Southern China. Four design options were evaluated in this study, such as, PV/C case – the air gap remains open at all sides, the PV/T case – the air gap only open at the top and bottom ends, BiPV case – the panels are mounted directly to the external wall and finally the base case – bare panel for evaluation and comparison purposes. The results shows that no significant differences in electrical output for three cases. In term of effectiveness in space heat gain reduction, the PV/C and PV/T cases are much better compared to other cases. They concluded that by cooling the PV effectively can increase the PV electricity output.

Pareto and Pareto [4] mentioned that energy in general is important not only to the country and the economy but also important to the population growth. In addition to population growth, economic expansion led to faster growth in energy consumption. The urbanization development is one of the factors that influenced the increases of the energy usage in any society. The usage of domestic energy such as electrical and thermal in residential and commercial area is one of the key factors to the development of building integrated photovoltaic/thermal or in abbreviation, knows as BIPVT. BIPVT combined and blend the building structure with the PV/T system. In here, PV/T system can be installed on the roof of a building as a roofing material to replace the common roofing material available in the market. By integrating and blending the PV/T system, not only inherit the advantages of PV system, also reduce the payback period of the building. Moreover, it can improve the aesthetic look of a building and minimizing the space for installation. Christandonis [24] mentioned that the use of PV/T systems in residential can contribute to the reduction of the energy consumption for heating, cooling and at the same time minimizing the total surface area of the system. Minimized the usage of the installation area will maximizing energy gained per unit surface area and it is consider as an economical way to produce energy.

A theoretical study on collectors consist of thermal collector attached to laminated photovoltaic module has been performed [69]. Their main objective of the study is to improve the efficiency of the electrical efficiency by reducing the photovoltaic temperature and use it for domestic cooling heating and cooling demands. In this study, they suggested that in order to obtain good result, parameters such as variation of geographical region (in Greece) and different total surface area of the system need to be investigated further. Results from this study clearly show that both mentioned parameters have significantly affected the solar coverage percentage of the system. They believed that PV/T technology is the best solution to the domestic heating and cooling for future energy consumption for house.

An interesting attempt has been made by Anderson et al. [70] to integrate the PV/T system to a building. In this experiment, a PV cells are laid onto a standing seam or toughed sheet roof using a laminated technique to form a BIPVT system. The BIPVT system designed allowed the water to pass through underneath the cells to generate hot water when exposed to the heat from the sun. The results from this experiment show that the design parameters includes the fin, the conductivity between the cells and the roofing material and also laminating technique, influenced the BIPVT system. They strongly believed that the BIPVT could be made cheaper even using a common pre-coated color steel material.

A theoretical investigation of the performance of double facades with integrated photovoltaic and motorized blinds has been performed by Charron and Athienitis [71]. The theoretical investigation has been performed to show the important and

the benefits of general guidelines to a facades design that lead to the BIPV/T applications.

An approach using TRNSYS software to analyze the thermal modeling of a building with an integrated ventilated PV façade has been performed by Mei et al. [72]. Another simplified approach to calculate the thermal performance of building integrated mechanically ventilated PV facades has been performed by Infield et al. [73] and they presented the simplified approach in a form of methodology for calculating the thermal impact on building performance.

Interesting study has been performed by Guiavarch and Peuportier [74] and discovered that the productivity and efficiency of the PV is depends on the type of integration. They point-out that by fixing the PV collector on a façade of a building without any ventilated air gap will reduces both productivity and efficiency of the modules. They suggested that the PV collector should be coupled with an air collector to increase its efficiency.

4. Conclusions

This paper has been presented with the comprehensive review on the description on design configurations of flat plate PV/T collector systems. This paper also convoluted the principle classifications of flat plate PVT collector systems. This classification provides clearly how this flat plate PV/T collector system designed can be grouped systematically according on the type of working fluid used such as water or air. Moreover, the flat plate PV/T collector system can be further distinguished according to the flow pattern of the absorber collector underneath the flat plate module. For flat plate PV/T water type, it can be distinguished by the water flow pattern usually installed underneath the flat plate and can be in sheet and tube, square/rectangular or round shape. For flat plate PVT air type, it can be distinguished according to the air flow pattern and can be installed above, below or on both sides of the absorber collectors. The flat plate PV/T air type can also be combined with water type. The flat plate PVT collector systems inherit the benefits of PV module. It works on noiseless environment; do not produce any unwanted waste such as radioactive materials, highly credibility system with life span expectation is between 20 and 30 years and very low maintenance cost and suitable for the application of building integrated photovoltaic/thermal system (BIPVT). In conclusion, the PV/T can be improved further based on few suggestions, such as:

- New design of absorber collector to improve efficiency of the PV.
- Replacing the roofing material with new material that will increase the efficiency of the system and at the same time reduces the payback period – attractive in case the available roof surface is limited.
- Payback – proposed system that gain pay back in less than 10 years.
- Production and installation cost – new method to integrate the systems into one product with value added production.
- Sustainable Energy – ensure that the energy produced by the system is sustainable with zero CO_2 emissions.
- Aesthetics – integration rather than "bolt on roof" gives better architectural look.

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